THE XYZs OF CHARMONIUM AT BES

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This contribution reviews some recent developments in charmonium spectroscopy, and discusses related theoretical predictions. The spectrum of states, strong decays of states above open charm threshold, electromagnetic transitions, and issues related to the recent discoveries of the "XYZ" states are discussed. Contributions that BES can make to our understanding of charmonium and related states are stressed in particular.

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I. INTRODUCTION

The spectroscopy of mesons containing charmed quarks has been the subject of intense interest since the discovery of the surprisingly light and narrow $c\bar{s}$ candidates $D_{s0}(2317)$ and $D_{s1}(2460)$ at BABAR [1] and CLEO [2] respectively. These states and other recent developments in charm meson spectroscopy have been reviewed by Swanson [3].

These discoveries demonstrated that the "naive quark potential model", which assumed that these mesons could be reasonably well described as $q\bar{q}$ bound states moving in a simple confining potential (typically a Coulomb plus linear form, augmented by spin-dependent forces from one gluon exchange and scalar confinement), was much less accurate in some heavy quark systems than had previously been thought. For example, the $c\bar{s}$ scalar D_{s0} state had been expected at 2.48 GeV in the potential model of Godfrey and Isgur [4], about 160 MeV above the mass of the $D_{s0}(2317)$; previous to this discovery, mass discrepancies in the charmed sector were anticipated to be perhaps a few 10s of MeVs. It is now widely accepted that the dynamical reason for this discrepancy is the strong coupling to the nearby S-wave decay channel DK at 2360 MeV, which suggests that the valence $(q\bar{q})$ approximation for hadrons can be misleading, and continuum components in charmed meson states may be surprisingly large. In the extreme case this might even suggest DK molecular states [5]; an accurate measurement of the partial width of the radiative transition $D_{s1}(2460) \to D_s\gamma$, which has been observed by BABAR [6], may be used to test the conventional $c\bar{s}$ model. In all these cases of strongly coupled valence states and hadron continua, both types of basis states are of course important, and both should be included in models of the hadronic state vector.

These discoveries dramatically illustrate the crucial importance and richness of experiments on the spectroscopy of heavy-flavor hadrons, where striking and unexpected discoveries have been made repeatedly in recent years.

II. CHARMONIUM

Charmonium spectroscopy has also been a very active topic recently. The realization that studies of B decays could make important contributions to charmonium spectroscopy [7] was followed by the discovery of the remarkable X(3872) state by the Belle Collaboration at KEK [8], in the final state $J/\psi\pi^+\pi^-$. Although it was initially thought that this might be one of the as yet undiscovered narrow D-wave 2^- states, the mass and width were found to be inconsistent with this assignment [9].

The near degeneracy of the X with the mass of a neutral D^0D^{*0} pair suggested that this might instead be an S-wave DD^* molecule, strongly isospin violating since it would be largely a neutral pair [10, 11]. One would expect a weakly bound DD^* system if bound by pion exchange [12] to have $J^{PC} = 1^{++}$ quantum numbers, and there is now much evidence that this J^{PC} assignment is correct [13]. The recent observation of the X(3872) with comparable strength in the two modes $J/\psi\rho^0$ *and* $J/\psi\omega$ [14] is the most striking evidence of the validity of this D^0D^{*0} charm molecule model. Thus the early speculations [15, 16] that there might be charmed meson molecules appear to be confirmed, although not the $\psi(4040)$ as was originally suggested.

The surprises in charm-strange meson spectroscopy and the discovery of the X(3872) motivated several recent detailed theoretical studies of charmonium spectroscopy [17, 18]. The known spectrum of charmonium candidates has until recently been in remarkably good agreement with potential model predictions; Fig. 1 for example shows the charmonium spectrum in a Coulomb plus linear potential model (abstracted from Ref.[17] and updated) compared to experiment. Studies of the strong decays of states above the open-charm threshold of 3.73 GeV [17, 18] showed that in addition to the narrow 2^{-+} and 2^{--} states, the 3^{--} $^3D_3$ $c\bar{c}$ state should also be quite narrow (< 1 MeV) due to the large F-wave centrifugal barrier against its decay mode DD. All of the allowed open-charm strong decay amplitudes and E1 electromagnetic partial widths of the $c\bar{c}$ states up to 4.42 GeV were evaluated in these theoretical studies, and future comparisons of these predictions with experimental results will provide interesting tests of our understanding of the physics of charmonium.

We note in passing that there are more fundamental studies of charmonium using lattice QCD, which thus far have found results for the spectrum of states that are quite similar to the predictions of potential models. This work was reviewed at this meeting by Morningstar [19].

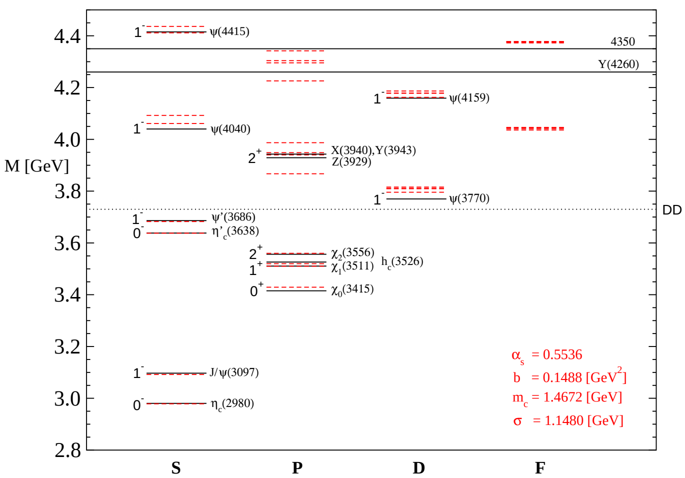

FIG. 1: The current experimental status of charmonium (and possible charmonium hybrid) spectroscopy, compared to the predictions of a nonrelativistic potential model. Experimental levels are solid lines, and theoretical levels are dashed. The open-charm threshold at 3.73 GeV is also shown.

A. The XYZ States Near 3.9 GeV

Three of the states discovered in recent experimental studies, the X(3943), Y(3940) and Z(3930), have masses roughly consistent with expectations for 2P states (radial excitations of the $\{\chi_J\}$) and perhaps the 3S η_c''; see Fig. 1. These obvious $c\bar{c}$ assignments should be explored in detail before more exotic interpretations such as molecules or anomalously light $c\bar{c}$ hybrids are seriously entertained.

TABLE I: Allowed open-charm decay modes and partial widths (^{3}P$_0$ model) of $C = (+)$ 2P $c\bar{c}$ states.

State	Quantum Numbers	Mode	Width (MeV)
$\chi_2'(3929)$	$2^3\mathrm{P}_2$ (2^{++})	DD*	11.3
		DD	34.3
$\chi_1'(3940)$	$2^3\mathrm{P}_1$ (1^{++})	DD*	140.
$\chi_0'(3940)$	$2^3\mathrm{P}_0$ (0^{++})	DD	see text

Since the only open-charm strong decay modes available these states are DD and DD*, a simple comparison of the states observed in these two decay modes can provide valuable information. The predicted partial widths of 2P states into these modes in the ^{3}P$_0$ decay model of Ref.[17], generalized to the masses indicated, are given in Table I. Note that the width of the χ_0' is problematic, as there is a node in the ^{3}P$_0$ model DD decay amplitude near the physical point.

1. *Z(3930)*

Of the three new XYZ states, the Z(3930) and its proposed assignment should be the easiest to test in future experiments. This state was reported by the Belle Collaboration [20] in $\gamma\gamma$ collisions, in the processes $\gamma\gamma \to \mathrm{Z}(3930) \to \mathrm{D}^+\mathrm{D}^-$ and $\mathrm{D}^0\bar{\mathrm{D}}^0$. Belle suggested that this might be the radially excited J=2 χ_2', since there is a preference for J=2 in the DD angular distribution.

The reported strength of the combined $\gamma\gamma$ and DD couplings is indeed roughly consistent with this χ_2' assignment. The published [20] Belle results are

$$M = 3929 \pm 5 \pm 2 \; MeV, \tag{1}$$

$$\Gamma = 29 \;\pm\; 10 \;\pm\; 2 \; MeV \tag{2}$$

and

$$\Gamma_{\gamma\gamma} \cdot B_{DD}\Big|_{expt.} = 0.18 \pm 0.05 \pm 0.03 \; keV. \tag{3}$$

In comparison, the quark model predicts a two-photon width for a χ_2' of about $\Gamma_{\gamma\gamma} = 0.64$ keV [21] (Münz [22] quotes theoretical results for this number from several models, which give $\Gamma_{\gamma\gamma} = 0.317 - 0.684$ keV), and a DD branching fraction of about 75%. (This DD branching fraction is from the ^{3}P$_0$ decay model of Ref.[17], generalized to a χ_2' mass of 3.929 GeV.) Combining the $\Gamma_{\gamma\gamma}$ range quoted by Münz and the predicted DD branching fraction gives the theoretical result

$$\Gamma_{\gamma\gamma} \cdot B_{DD}\Big|_{theor.} = 0.24 - 0.51 \; keV. \tag{4}$$

Given the uncertainties in these calculations, this may be regarded as rough agreement between theory and experiment for a χ_2'. The definitive test of this assignment would be the observation of a DD* mode; the expected relative branching fraction is DD*/DD = 0.35, and the only plausible competing assignment, 0^{++} $2^3\mathrm{P}_0$, does not lead to a DD* final state. (The 1^{++} $2^3\mathrm{P}_1$ of course cannot be made in $\gamma\gamma$ collisions.)

2. X(3943)

The X(3943) was reported by Belle [23] in the double charmonium production reaction $e^+e^- \to J/\psi$ X(3943) in the final state DD*, in both charged and neutral modes. The fitted mass and width are

$$M = 3943 \pm 6 \pm 6 \ MeV, \tag{5}$$

$$\Gamma = 15 \pm 10 \ MeV \text{ or } < \ 52 \ MeV \ (90\% \ c.l.). \tag{6}$$

Since the only other charmonium states seen recoiling against the J/ψ with comparable strength in this (poorly understood) process are the η_c, χ_0 and η_c', the obvious assignment for this state is η_c''. (χ_0' cannot decay to DD*).

The reported total width however is surprisingly small for an η_c'' assignment; one expects $\Gamma = 70 \ MeV$ in the ^{3}P$_0$ decay model, using the reported mass as input. Of course the experimental total width is not very well determined, and the discrepancy may disappear with better statistics. The mass is also surprising for an η_c'', since it is about 100 MeV below the presumably 3^3S$_1$ partner $\psi(4040)$; in the 2S states, the $\psi'-\eta_c'$ splitting in contrast is only about 30 MeV. If the X(3943) is indeed the η_c'', either the mass is not yet accurately determined, or there are important mass shifts in the 3S states relative to 2S. Testing the η_c'' assignment is a simple matter of establishing whether the angular distribution of DD* final states is P-wave (J^P = 0$^-$); alternative J=1 and J=2 2P assignments lead to S- and D-wave DD* final states.

3. Y(3940)

This may be the least well established of the new XYZ states. Evidence for this state was reported by Belle [24] as an $\omega J/\psi$ threshold enhancement in the charged B decays B$^\pm \to$ K$^\pm \omega J/\psi$. Assuming that this was due to a resonance, Belle quoted a mass and width of

$$M = 3943 \pm 11 \pm 13 \ MeV, \tag{7}$$

$$\Gamma = 87 \pm 22 \ MeV. \tag{8}$$

Of course the observation of a charmonium state in a closed-charm final state such as $\omega J/\psi$ with a relatively large branching fraction ($B_{B\to KY} \cdot B_{Y\to\omega J/\psi} = 7.1 \pm 1.3 \pm 3.1 \cdot 10^{-5}$) is very surprising, since the corresponding close-charm decay partial width for $\psi' \to J/\psi\pi\pi$ is only about 140 keV. Since the Y(3940) has a total width near 100 MeV, one might expect an $\omega J/\psi$ branching fraction of roughly 10^{-3}. Since the known *total* B meson branching fractions to the 1P $c\bar{c}$ states such as the χ_1 are only an order of magnitude larger, for example $B_{B\to K^+\chi_1} = 5.3 \pm 0.7 \cdot 10^{-4}$, the reported Y(3940) signal appears to imply an anomalously large branching fraction for Y(3940) $\to \omega J/\psi$. Either the Y(3940) is quite unusual in populating this decay mode, or it is not actually due to a resonance.

The mass, width and $\omega J/\psi$ decay mode of this state, and the fact that the 2^{++} 2P state is likely the Z(3930), suggest that the least implausible $c\bar{c}$ assignment for the Y(3940) is 1^{++} 2^3P$_1$. This state is predicted to have a total width of about 140 MeV, dominantly into the open-charm mode DD*. A search for this signal in DD*, with a much larger branching fraction than $\omega J/\psi$, is the obvious test of this assignment. If this assignment is correct, the closed-charm mode $\omega J/\psi$ may have come about through an inelastic final state interaction, Y(3943) $\to$ (DD*, D*D*) $\to \omega J/\psi$. The fact that these are near-threshold S-wave processes would enhance this FSI effect.

III. FUTURE BES CONTRIBUTIONS

As an e^+e^- machine in the E$_{cm} \approx$ 3-4 GeV mass range, the contribution of BES to these studies of charmonium and related states will usually involve the initial production of a 1^{--} resonance. The four known 1^{--} states with relatively large e^+e^- couplings are the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$. As the physics questions that can be addressed using each of these entry states differ somewhat, we will briefly discuss them individually here.

A. $\psi(3770)$

The $\psi(3770)$ is a well established, dominantly D-wave $c\bar{c}$ state. One topic of interest here is the level of ^{3}S$_1$-^{3}D$_1$ mixing present in the $\psi(3770)$; a moderate mixing is required to explain the e^+e^- width of this state, since a pure D-wave $c\bar{c}$ would have a much smaller e^+e^- width than is observed. There is a cross-check of this mixing angle using E1 radiative widths; the partial width for $\psi(3770) \to \gamma\chi_2$ is very sensitive to this mixing angle [17, 26], and recent upper limits from CLEO-c are rather close to the expected width [25]. It would be very interesting for BES to measure this E1 width. The remaining transitions $\psi(3770) \to \gamma\chi_{0,1}$ are also interesting as checks of the theory, but are much less sensitive to this mixing angle.

Another very interesting question that can be addressed using the $\psi(3770)$ is the strength of the coupling of orbitally excited $c\bar{c}$ states to $p\bar{p}$. This is a very important question for the future PANDA experiment [27] at GSI, which plans to use $p\bar{p}$ annihilation to produce excited $c\bar{c}$ and charmonium hybrids. At present we have the intriguing experimental observation that the L=1 $c\bar{c}$ χ_J states couple much more strongly to $p\bar{p}$ than the L=0 J/ψ, but whether this trend continues to L=2 is an open question. BES can easily answer this question through a high-statistics search for $\psi(3770) \to p\bar{p}$. Three body decays such as $\Psi \to p\bar{p}m$ (where Ψ is a generic charmonium or charmonium hybrid resonance and m is a light meson) are also very interesting in this regard, and can be used to estimate the associated production cross section for $p\bar{p} \to m\Psi$ (see Ref.[28]); this reaction will be used by PANDA to search for J^{PC}-exotic charmonium hybrids.

B. $\psi(4040)$ and $\psi(4160)$

The $\psi(4040)$ and $\psi(4160)$ have important applications in the study of the open-flavor strong decay mechanism, and are also of interest because their radiative transitions can be used to access lower-mass $c\bar{c}$ candidates such as the new XYZ states.

1. *Strong Decay Studies using D^*D^**

The strong decays of the vectors $\psi(4040)$ and $\psi(4160)$ to D^*D^* are especially interesting, since this is their only "multiamplitude" decay mode. The decays to DD and DD^* are single amplitude decays, respectively $^1P_1$ and $^3P_1$, so one learns nothing new about the decay process by studying their angular distributions. The decays to D^*D^* however have three allowed amplitudes, $^1P_1$, $^5P_1$ and $^5F_1$, and an experimental determination of the ratios of these amplitudes can be used as an important test of the decay model, specifically of the quantum numbers of the light $q\bar{q}$ pair produced in the decay. The two principal models assumed by theorists to study these $c\bar{c}$ decays at present are the $^3P_0$ (scalar) model [17] and the Cornell (timelike vector) model [18]; these give different predictions for the relative D^*D^* decay amplitudes, which have not been tested experimentally. Of course these quantum numbers are not especially fundamental, and many other possibilities can be imagined. In the $^3P_0$ model, the P-wave $\psi \to D^*D^*$ decay amplitudes have simple ratios [17] that are independent of the radial wavefunction, $^5P_1/^1P_1 = -2\sqrt{5}$ for an initial S-wave ψ state and $^5P_1/^1P_1 = -1/\sqrt{5}$ for an initial D-wave. An S-wave ψ gives a vanishing $^5F_1$ D^*D^* amplitude, whereas for a D-wave it is large. (For a pure D-wave $\psi(4160)$ this $^5F_1$ D^*D^* amplitude is predicted to be dominant.)

If BES can measure these amplitude ratios, this important information will allow theorists to formulate more accurate models of $c\bar{c}$ strong decays, and should greatly improve our understanding of this dominant QCD strong decay process generally.

2. *Accessing the XYZ States*

The $\psi(4040)$ and $\psi(4160)$ can be used as 1^{--} entry states for the study of the new XYZ states near 3.9 GeV. As shown in Table II, both these states are expected to have relatively large E1 branching fractions into the 2P $c\bar{c}$ multiplet, $\psi(4040, 4160) \to \gamma\chi'_J$. (These E1 partial widths were calculated as in Ref.[17], for the masses given in the table.) This may allow the identification of the 2P resonances through their subsequent hadronic decays. In this approach one would study the invariant mass and angular distributions of the final charmed mesons in the processes $e^+e^- \to \psi(4040, 4160) \to \gamma DD$ and γDD^*.

TABLE II: Theoretical E1 radiative partial widths of the $\psi(4040)$ and $\psi(4160)$ into $C = (+)$ 2P $c\bar{c}$ states.

Initial State	Final State	E1 Width (keV)	E1 B.F.
$\psi(4040)$	$\chi'_2(3929)$	56.	$0.7 \cdot 10^{-3}$
	$\chi'_1(3940)$	25.	$0.3 \cdot 10^{-3}$
	$\chi'_0(3940)$	8.3	$0.1 \cdot 10^{-3}$
$\psi(4160)$	$\chi'_2(3929)$	9.9	$0.1 \cdot 10^{-3}$
	$\chi'_1(3940)$	129.	$1.3 \cdot 10^{-3}$
	$\chi'_0(3940)$	172.	$1.7 \cdot 10^{-3}$

C. States above 4.2 GeV

The recently discovered 1^{--} states Y(4260) [29, 30] and the (post conference) new state at 4350 MeV [31] are strictly speaking not within the assigned topic of this talk; since the previously known 1^{--} states $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ fill the available 1^{--} $c\bar{c}$ assignments to just above 4.4 GeV, these two new states appear unlikely as $c\bar{c}$ candidates. They have been reported only in the closed-charm modes $J/\psi\pi\pi$ and $\psi'\pi\pi$ respectively, which are naively expected to be very weak. (Of course there is a LGT prediction that hybrids might preferentially populate these modes [32].) Here the most important task is probably to search for these states in all accessible open-charm modes, which might be expected to be dominant even in hybrids.

Finally, the highest-mass $c\bar{c}$ state currently known is the 1^{--} $\psi(4415)$, which is usually given a 4^3S_1 assignment. Nothing is currently known about its exclusive decay modes. (The PDG [33] says that the $\psi(4415)$ decays dominantly to "hadrons", which is not especially surprising.) Calculations of the decay branching fractions of a 4^3S_1 $c\bar{c}$ $\psi(4415)$ in the $^3P_0$ model [17] predict that the largest mode should be the unusual DD_1, and in pure D-wave rather than S-wave! It would clearly be a very interesting test of strong decay models to measure the strong decay amplitudes and branching fractions of this state. There is also an "industrial" application of the $\psi(4415)$; by running on the high mass tail of this resonance, one can expect a relatively large branching fraction into the enigmatic $D_{s0}(2317)$ [17, 34], which otherwise is very difficult to produce with useful statistics. A study of interesting decays such as the radiative branching fraction of the $D_{s0}(2317)$ into γD_s^* could then be carried out at BES; this would be valuable in determining the relative size of the $c\bar{s}$ and DK components of the $D_{s0}(2317)$.

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